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‘All sunshine makes a desert’. Building interdisciplinary understanding of survival strategies of ancient communities in the arid Zerqa Triangle, Jordan Valley☆

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ABSTRACT

Archaeological studies typically describe arid areas as extremely unpleasant areas for human occupation and use. Without suggesting that arid areas are pleasant places, however, this paper provides a reassessment of the meaning of aridity for an area showing a vast amount of evidence of (past) human activities. Several climatic proxy data suggest that at the transition between the late Bronze Age and the Early Iron Age (around c. 1300-1100 BC) the southern Levant witnessed more arid conditions, while after 1100 BC relatively moist conditions would have prevailed. In drylands, small changes in temperature and water availability can have large effects on subsistence options. Building on cooperation between an archaeologist and a water scholar, this paper offers an approach to study how people in the past were able to craft a livelihood in the arid environments in the southern Levant and elsewhere. Focusing on the Zerqa area, the paper explores the potential of this cooperation by studying effects of climatic changes at the transition from the Late Bronze Age to the Iron Age through a modelling approach. Changes in temperature and moisture availability were simulated, showing that increased aridity could have been met by either naturally available water (especially groundwater) or artificially added water (although the timing appears to be crucial). While the model approach under discussion offers an approximation of the past, it shows the potential impact of climatic changes on the subsistence of past communities. It shows that details can mean the difference between survival or collapse.

1. Introduction

Arid areas are difficult to create a livelihood in, but archaeological remains show many of these areas have been intensively inhabited in the past. People have obviously succeeded in devising strategies to survive in areas that outsiders often regard as very inhospitable. However, climate is not fixed or unchanging. One of the main questions archaeologists studying societies in arid environments try to answer is how people in arid environments were able to create a sustainable mode of subsistence and how resilient their societies were to environmental changes. By looking outside the boundaries of archaeology and joining forces with disciplines like irrigation engineering, a better understanding can be gained about the potential impact of climatic changes on ancient communities. We demonstrate the potential of such cooperation in this article, in which we investigate what impact the climatic changes evidenced at the end on the Late Bronze Age may have had on the inhabitants of the Zerqa Triangle and how these inhabitants could have responded to the changes. By modelling hypothetical water availability and resulting crop yield, we can build a better understanding of the potential for crop cultivation and changes therein given climatic changes. This type of information is essential for archaeologists trying to explain changes in settlement pattern and subsistence in past societies.

One of the periods where considerable climatic fluctuation has been attested is the end of the Late Bronze Age (c. 1300-1100 BC). This is a period of crisis, upheaval, and unrest throughout the entire eastern Mediterranean. For about 1.5 centuries the entire area encompassing the Aegean, Anatolia, Cyprus, the Levant, and Egypt witnessed a period of economic crisis, mass migrations, famine and the destruction of numerous urban centres (Ward and Joukowsky, 1992; Cline, 2014). Several different hypotheses have been proposed as the origin of this crisis: a wave of earthquakes (Nur and Cline, 2000), climate change,

☆ Arab proverb - أشعة الشمس في كل وقت يجعل الصحراء.

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economic collapse. Recently, most hypotheses focus on series of connected events triggering and aggravating each other (a domino effect) with climatic change as one of the factors (e.g. Langgut et al., 2013). Although the debate is ongoing, a large and still growing amount of climatic proxy data as well as historical sources point to a more unstable and drier climate between the 13th and 10th centuries BC (Knapp and Manning, 2016: 138).

While the entire eastern Mediterranean is affected by the Late Bronze Age crisis, not all areas or communities were impacted in the same way. In the coastal area of the southern Levant, for example, the large urban centres are destroyed, but rural villages continued (Finkelstein, 2003; Langgut et al., 2013). It this heterogeneity a reflection of the different effects climate change had on environmentally diverse regions or are social factors at play? The increasing aridity will have had far greater impact on communities inhabiting the fringes of cultivable land than on people living well within the margins of the dry farming area. In order to be able to evaluate the differential weight of all proposed factors at play in the Late Bronze Age crisis, the impact of climatic changes should be much better understood. In this article we provide a first attempt by modelling the impact of climatic changes on the marginal Zerqa Triangle in Jordan.

The Zerqa Triangle (see Fig. 4) has been well investigated archaeologically and we have a good understanding of the communities at the transition between the Late Bronze Age (1550-1200 BC) and the Iron Age I (1200-100 BC) and II (100-750 BC) (Kaptijn, 2009a; 2009b; Van der Kooij, 2006, 2007; Petit, 2009). While the Zerqa Triangle is on the very edge of the dry farming zone, archaeological research has attested that people had found a way to extend this zone by means of an irrigation system. We do not known, however, how robust and reliable this irrigation system was and when it started precisely. Would a decline in annual rainfall of 50 or 100 mm a year jeopardize the subsistence of these communities? In this article we try to determine to what extent the attested aridification would have affected the inhabitants of the Zerqa Triangle. Below, we first discuss the evidence available for climatic changes in the region, followed by an overview of the archaeological record in the Zerqa Triangle. Then we discuss our analysis of impacts of climatic changes on agriculture and options for farmers to respond. We conclude with some observations how this interdisciplinary approach would enhance our understanding of arid regions under climatic change in the archaeological record.

2. Climate

Several climate proxy records in both the southern Levant and the wider region attest a period of climatic changes around ca. 1300-1000 BC. In the North Atlantic, this period is marked by the Rapid Climate Change event of c. 1200 cal. BC, which is characterized by stronger Siberian Highs (Mayewski et al., 2004). These higher temperatures resulted in the more than average melting of polar snow and ice - c. 1200 BC saw the highest temperature in five millennia in the Greenland ice cores (Langgut et al., 2013: 162). Cool water from the melting polar ice entered the oceans lowering the average temperature. This also impacted the eastern Mediterranean and cooler winter Sea Surface Temperatures have been attested in the Aegean (Finné et al., 2011; Drake, 2012). These cooler sea temperatures in turn lowered the evaporation rates thereby reducing the amount of moisture westerly winds carried to the southern Levantine coast which resulted in diminished precipitation (Drake, 2012: 1868).

Throughout the Eastern Mediterranean, evidence for a dry spell has been attested in the late second millennium BC, e.g. on the Syrian coast (Kaniewski et al., 2010), Cyprus (Kaniewski et al., 2013) and the Nile delta (Bernhardt et al., 2012). However, doubts have lately been cast on the dating precision of some of these studies arguing that these indications of drier circumstances could belong to a much wider timeframe (Knapp and Manning, 2016).

In the southern Levant, several climatic proxy records attest the arid

Fig. 1. The position of the Zerqa Triangle in the southern Levant and other locations mentioned in the text.

spell at the end of the Bronze Age. Pollen cores from the Sea of Galilee (Langgut et al., 2013), 70 km north of the Zerqa Triangle, and from two locations on the shores of the Dead Sea (Neumann et al., 2010; Litt et al., 2012; Langgut et al., 2014), 50 and 85 km south of the Zerqa Triangle respectively, demonstrate a sharp decrease in number of arboreal pollen (Langgut et al., 2015: 228) (see Fig. 1). Mediterranean tree species such as *Quercus ithaburensis*, *Quercus calliprinos*, and Pistacia drop dramatically to values below 1% (Litt et al., 2012). At the same time, herbaceous species, usually taken to represent more arid conditions, reach a maximum, e.g. in the Dead Sea cores of Ze'elim and Ein Feshkha (Neumann et al., 2010: 760). As the number of anthropogenic indicators is also low, e.g. low olive pollen, the authors conclude that the drop in arboreal pollen is climate-related instead of resulting from human-induced deforestation (Langgut et al., 2015: 229). At Birket Ram in the Golan hills the suggested arid period is much less intense and only a low drop in arboreal pollen is visible (Neumann et al., 2007: 337). The drop in arboreal pollen in Sea of Galilee core has been dated to the mid-13th century BCE until end 12th century BCE, while the period continues slightly longer in the Ein Gedi core (Langgut et al., 2015: 228).

Geological archives that document the lake levels of the Dead Sea also suggest a period of aridification. These attest to a severe drop in lake levels at the start of the Late Bronze Age (Kagan et al., 2015). The lowest level was identified at 415 m bmsl and dated to 1562–1435 cal BC (the present level is 418 m bmsl) (Kagan et al., 2015: 247). Within c. 200 years lake levels dropped by 45 m (Migowski et al., 2006: 426, Fig. 6). A recent study of climatic fluctuations in the Dead Sea basin dates the arid period and low lake level between c. 1500-1300 cal BC based on varve counts and radiocarbon dates of two high resolution

cores (Neugebauer et al., 2015). At Soreq cave, located c. 10 km west of Jerusalem, stable oxygen isotope data suggest stable arid conditions with only minor fluctuations (Bar-Matthews et al., 2003: Fig. 6). Unfortunately, in the Soreq cave data this period is characterized by a low resolution of as much as 102 years per data point.

A critique on the dating precision of the Sea of Galilee pollen core has recently been put forward (Knapp and Manning, 2016: 114, Fig. 6). Reanalysis of the six radiocarbon dates using a different age-depth model and including the possibility of non-uniform deposition rates suggest that the end of the Late Bronze Age (c. 1200 BC) is represented by almost 1.5 m of sediment core (at 95.4% probability) instead of 20 cm (Knapp and Manning, 2016: 114). While Langgut et al. identify the arid end of the Late Bronze Age at a depth of 625-599 cm and a date between 1250 and 1150 cal. BC, the reanalysis provides a date of 1450-1033 cal BC at 68.2% probability and 1665-765 cal. BC at 95.4% probability for the arid episode (Knapp and Manning, 2016: 144, 116). Similar issues have been raised regarding the dating precision of the cores from Cyprus and the Syrian coast (Knapp and Manning, 2016: 102–107). This is of course problematic for the study of the Late Bronze Age crisis. For our study, however, the precise dating of one set of proxy data is of lesser relevance as we investigate the potential impact of climate change. Furthermore, even Knapp and Manning who voiced this critique agree that it is remarkable that so many climatic proxy data and historical sources suggest a period of aridification between the 13th and 10th centuries (Knapp and Manning, 2016: 138).

3. The Zerqa triangle

3.1. The regional/social setting

The Zerqa Triangle is located on the eastern *ghor* of the Jordan Valley about halfway between Lake Tiberias in the north and the Dead Sea in the south. This name denotes the triangle formed by the streambed or *zor* of the river Jordan in the west, the Zerqa river in the southwest and the Wadi Rajib in the north. The *zor* is located 50–70 m below the *ghor* and farmers in the *ghor* can therefore not benefit from Jordan river water. The area consists of the saline Late Pleistocene Lake Lisan marls, that surface in several areas (see Fig. 2), with alluvial red-brown clayey/sandy loams on top (Hourani, 2010: 124).

Today, the region receives on average 260 mm of annual precipitation. It is generally considered that 250 mm is the threshold of dry farming (Wirth, 1971: 92). However, the low altitude (c. 250 m below sea level) and high temperatures (39 °C. av. summer temperature and 19 °C. av. winter temperature) result in a high potential evapotranspiration rate. Moreover, during the summer months from May to mid-October there is no rainfall whatsoever (see Fig. 3). Furthermore, there is a high interannual variation in precipitation with every three to five years, a year that receives about 100 mm less rainfall than the average (Jordan Meteorological Department). Without the supply of additional water these years would typically produce failed harvests.

The research area is located on the boundary between the Irano-Turanian zone and the Sudanian zone. The Irano-Turanian zone is characterized by plants that can withstand the continental steppe climate with low precipitation, hot summers and cold winter. Typical plants are steppe grasses and shrubs, like Artemisia herba-alba (white wormwood), with scattered pistachio and juniper trees (Soto-Berelov, 2015: 96). The Sudanian vegetation zone displays a tropical vegetation with plants, like acacias and *Ziziphus spina-christi* (Christ's thorn jujube) suited to high temperatures and minimal precipitation (Soto-Berelov, 2015: 96) (see Fig. 1).

Geomorphological research conducted by Fouad Hourani has identified the presence of moist soils only in the Late Neolithic to Early Bronze Age I period deposits (c. 5400-3050 BC). All test trenches and sections in the Zerqa Triangle show a gradual decrease in secondary carbonate nodules and the disappearance of ferromanganese concentrations denoting improved drainage (Hourani, 2010: 133). Above

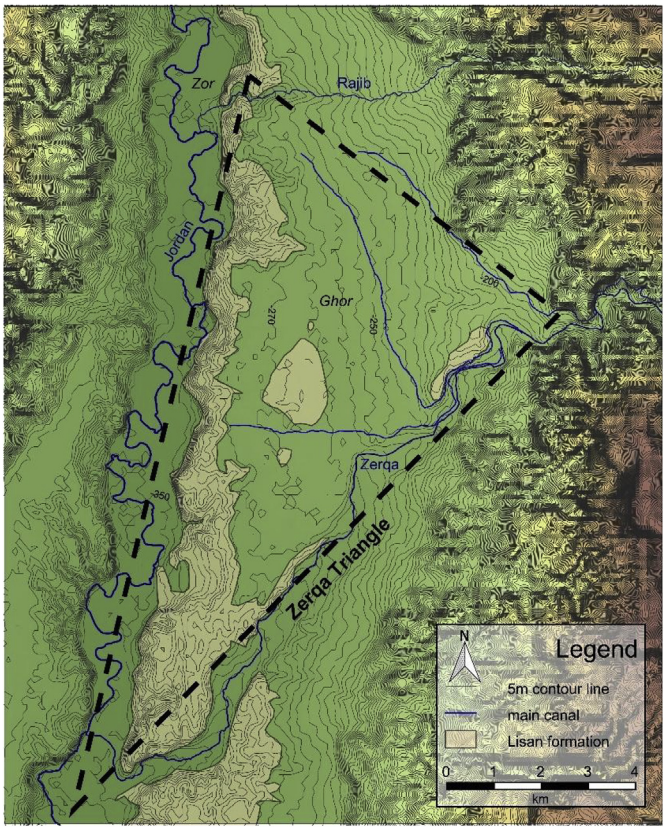

Fig. 2. Layout of the Zerqa Triangle.

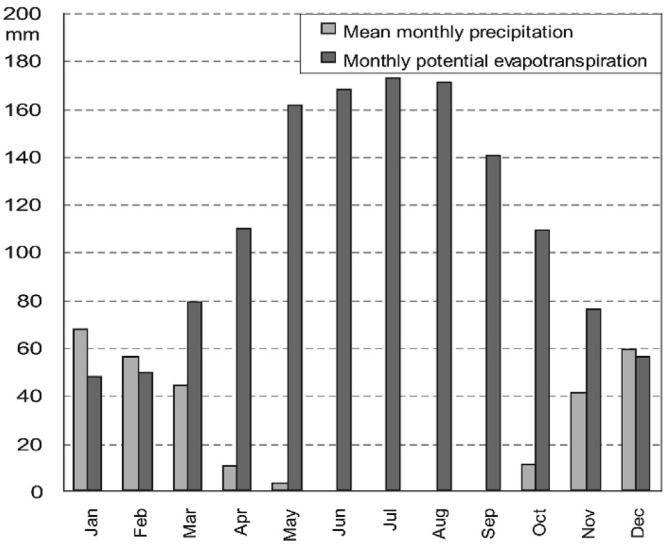

Fig. 3. Modern mean monthly precipitation and potential evapotranspiration according to the Penman-Monteith Equation at Deir 'Allā (data NCART Jordan and the Jordan Meteorological Department).

the well-watered Late Neolithic to Early Bronze Age I deposits several erosive episodes are visible that happened before the start of the Late Bronze Age, as the Late Bronze/Iron Age settlement of Tell Mazar (see Fig. 4) is located on top (Hourani et al., 2008: 432). Today, the Zerqa river is deeply incised. Normally, farmers can benefit from higher groundwater levels near the streambed of wadis or rivers. The severe downcutting of the Zerqa makes this impossible. Only 3 km after its entrance into the valley, the Zerqa is c. 10 m incised and at its entrance into the *zor* this altitude has increased to over 50 m. At the point where

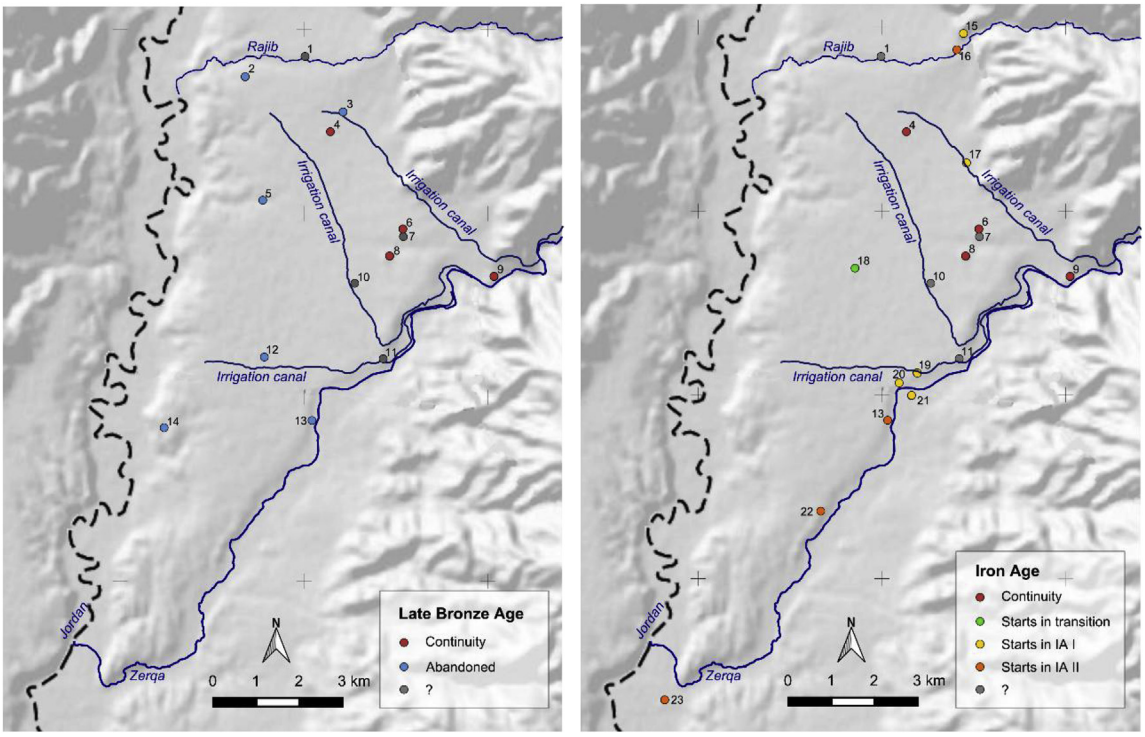

Fig. 4. Settlements in the Zerqa Triangle during the Late Bronze Age and Iron Age I and II (1- Khirbet Buweib, 2- Tell al-Kharābeh, 3- Tell al-Ghazāleh, 4- Tell al-Mazār, 5- 'Abū Nijrah, 6- Tell al-Qa'dān N, 7- Tell al-Qa'dān S, 8- Tell Deir 'Allā, 9- Tell al-Hammeh, 10- Tell al-Fukhār, 11- Tell al-Mīdan, 12- Tell al-'Arqadat, 13- Tell al-Zakarī, 14- Katāret es-Samrā', 15- al-Qōs, 16- Tell 'Ammata, 17- Tell al-'Adliyyeh, 18- Tell al-Khsās, 19- Tell al-Rkabī, 20- Tell al-Bashīr, 21- Tell al-Rmeileh, 22- Tell 'Umm Hammād, 23- Tell Dāmiyeh).

the Zerqa enters the *zor*, the Iron Age settlement of Tell Damieh is located. Geomorphological investigations at the foot of this site show that in the IA when the settlement was founded the Zerqa and Jordan rivers were already deeply incised and the surface was 3 m below that of today. This suggest major downcutting had already taken place before the Iron Age (Petit et al., 2006). No overbank deposits post-dating the Early Bronze Age I have been identified.

3.2. The LBA and IA transition

Over the past century the Zerqa Triangle has been thoroughly investigated archaeologically. As much as seven tell-oriented surveys have been carried out (for an overview see Kaptijn, 2009b; Petit, 2009: 155–159) and one intensive countryside survey (Kaptijn, 2009a). Of these tell surveys only Petit collected pottery in a systematic manner, meaning that he collected for a fixed amount of time and without focus on specific pottery types. Where possible, he divided the site in grids to estimate the size of the site in different times (Petit, 2009: 161–189). In this way, it is possible to get an understanding of the relative importance of different periods at a site. In the countryside survey the Late Bronze and Iron Age material was very limited, suggesting occupation only took place on tells in these periods (Kaptijn, 2009a: 191–197). Unfortunately, surveys cannot identify short periods of abandonment or decreasing occupation within a single period. This type of information can only be identified by excavation.

The sites in the Zerqa Triangle show a mixed signal in the period under study. Several sites contain pottery on the surface stemming from both the Late Bronze and Iron Ages. Based on these surface finds we assume that these sites were occupied in both periods and thus show continuity in this transitional period (see Fig. 4). Four sites show continuity (see Table 1). One of these sites, Tell al-Mazār, probably increased significantly in size and importance in the Iron Age (only few Late Bronze Age sherds were found) (Petit, 2009: 168; Yassine and Steen, 2012). However, there are six sites that were abandoned at the end of the Late Bronze Age or where Petit's systematic survey shows that the Iron Age is significantly less abundant (at Tell al-Kharābeh, Tell al-Ghazāleh and Katāret es-Samrā' Iron Age pottery is present on the surface, but only in very small quantities) (Petit, 2009: 164, 166, 176). At the same time as sites were being abandoned, the site of Tell al-Khsās was founded containing as oldest material ceramics dating to the transitional Late Bronze Age-Iron Age period (Petit, 2009: 170). After the transitional period, five new sites appeared in the Iron Age I and another three in the Iron Age II period. Tell al-Zakarī, abandoned in the Late Bronze Age, was reoccupied in the Iron Age II period. A few sites that become villages in the Iron Age, i.e. Tell Dāmiyeh, Tell 'Ammata and Tell al-Qōs, contain very low numbers of Late Bronze Age sherds (1–10 sherds, < 1%) on the surface. These numbers are too low to take as evidence for any significant permanent occupation. However, how these sherds should be interpreted remains unknown. The occupation history of five sites remains unknown. These sites were surveyed by the earlier surveys, with conflicting results, but could not be relocated or have since been destroyed. These sites are left out of consideration.

Based on the survey results, we thus see both continuity and

Table 1
Changes in the settlement pattern during the Late Bronze and Iron Ages (for locations see Fig. 4).

	No. of sites	Site names
Continuity	4	Deir 'Allā, Hammeh, Qa'dān N, Mazār
Abandonment	6	Kharābeh, Ghazāleh, Arqadat, Zakarī, Katāret es-Samrā', Abū Nijrah (?)
Starts in transitional LB-IA	1	Khsās
Starts in IA I	5	Bashīr, Rkabī, R'meileh, 'Adliyeh, Qōs
Starts in IA II	4	Ammata, Umm Hammād, Dāmiyeh, Zakarī
?	5	Qa'dān S, Nkheil, Buweib, Fukhār, Mīdan

abandonment at the transition between the Late Bronze Age and Iron Age. Unfortunately, these survey results do not show why sites are being abandoned or whether there are short hiatuses in occupation present. That type of information can only be attained by excavation and even then only in cases of good preservation. As many as 7 sites have been excavated, but unfortunately not all results have been fully published (Tell al-Hammeh, Tell umm Hammād) or excavations have not reached the layers dating to the LB-Iron Age transition (Tell 'Ammata, Tell Dāmiyeh, Tell al-Mazār) (Petit, 2009; Yassine and Steen, 2012) (for locations see Fig. 4).

At Tell Deir 'Allā, the Late Bronze and early Iron Age layers have been both excavated and published. While the survey remains suggest Tell Deir 'Allā was continually inhabited, the excavations show several different phases of occupation interspersed with destruction layers. During the Late Bronze Age Tell Deir 'Allā was a settlement of considerable size (phases B-D). While the settlement was probably almost continuously inhabited, several phases of collapse and rebuilding are visible together with a steady decrease in size (Van der Kooij, 2006: 223). In the last major Late Bronze Age phase (E), the site was probably a village containing a large sanctuary (Franken, 1992). This layer was completely destroyed by an earthquake and subsequent fire. Radiocarbon dates and a faience vase with a cartouche of the Egyptian queen Tawosret (1188-1186 BC) give a *terminus post quem* of ca. 1180 BC for the destruction (Vogel and Waterbolk, 1967; Franken, 1992: 177). The pottery of this phase shows clear, but not rigid differentiation to the preceding and succeeding periods (Van der Kooij, 2006: 219). This suggests both continuity and change. After the earthquake, the site was quickly rebuilt, but only provisionally (phase F) and was soon destroyed again. The site was left unoccupied for some time and when rebuilding took place (phase G) this was according to a different plan (Franken, 1992: 101) suggesting more significant change. Phase G was again destroyed by fire after which only squatter occupation amongst the ruins took place (Petit, 2009: 27). The first phases of the Iron Age (A + B) started around 1150 BC (Van der Kooij, 2006: 224) and saw bronze working and farming activities, but little architecture. The inhabitants of Iron Age phases A-D were most probably semi-nomadic and lived in tents (Van der Kooij, 2001: 296). In later phases of the Iron Age the quick oscillation between settlement and abandonment continues to characterize Tell Deir 'Allā, but now the settlements show more extensive and permanent architecture.

Excavations at Tell al-Hammeh have also reached Late Bronze Age levels. The small-scale rescue excavations conducted in 1996 and 1997 concluded that the Late Bronze Age habitation had only a temporary character and stemmed from an 'agro-pastoral, perhaps mobile, temporary population' (Van der Steen, 2004: 202). However, later excavations (2000, 2009) suggest more elaborate and permanent Late Bronze Age architecture was present elsewhere at the site. Unfortunately, the Late Bronze Age remains of these excavations have not been published.

Botanical samples from the excavated settlements show a range of crops were cultivated. Even though differential preservation rates have to be accounted for, the predominance of cereals (*Triticum aestivum/durum, Triticum* cf. *dicoccum, Hordeum vulgare*) seems to reflect past reality (Van Zeist and Heeres, 1973; Neef, 1989, 2012; Kaptijn, 2009a: 367). Other attested crops include chick pea, lentil, common pea, grass pea, bitter vetch, sesame, flax, herbs like fenugreek, cumin, coriander and fruits like grape, fig, and pomegranate (Van Zeist and Heeres, 1973; Neef, 1989, 2012; Kaptijn, 2009a: 367). As most of the sites in both periods are of a restricted size (< 1ha), and little social differentiation is visible, the terminal Late Bronze Age and Iron Age consisted most likely of a community of small-scale subsistence farmers (Kaptijn, 2009).

These excavation results show that the real habitation history is less static and continuous than survey results suggest. While Tell Deir 'Allā saw almost permanent activity, the settlement was abandoned, destroyed and reoccupied several times within a short time span. On the whole, the end of the Late Bronze Age does not appear to have been a stable period within the history of the region. Several sites get abandoned, but there is no complete collapse of the social structure in the region. This is visible in the sites that are inhabited throughout both periods and the material culture that shows several signs of continuity (Van der Steen, 2004: 186). The excavation results of Tell Deir 'Allā are insufficient to determine the character of society in the entire region during this transitional period, although several interesting hypotheses have been put forward (Van der Steen, 2004; Kafafi and Van der Kooij, 2013). Likewise, the evidence does not allow an encompassing explanation for the abandonment of sites (cf. the explanations of the LBA collapse; climate change, migrations, earthquakes, economic collapse). However, the earthquake attested at Tell Deir 'Allā will have impacted the entire region. Additionally, the region will have been affected by the decline in interregional contacts and trade resulting from the Late Bronze Age crisis in the wider region. However, the importance of this decline remains unknown. Most sites seem to have been small-scale and were probably involved in subsistence farming. If we want to better understand the difficulties and opportunities of these farmers during this period it is important to model the impact of increasing aridity on the agricultural activity in the region.

Table 2
The 25 years climatic series of series A. In series B temperature and potential evaporation remain constant.

Year	Rainfall (mm)	Temperatures (degrees Celsius)	Potential evaporation (mm)	General
1	Artificial daily patterns based on real data from 20th century	Monthly measured data	Monthly measured data	Random factor per year between 0,9 and 1,1 to include variation
2				
3				
4				
5				
6				
7				
8				
9				
10				
11				
12				
13	All daily events 1 mm less			
14				
15				
16				
17	All daily events 2 mm less	5% higher compared to base data	5% higher compared to base data	
18				
19				
20				
21	All daily events 3 mm less	10% higher compared to base data	10% higher compared to base data	
22				
23				
24				
25				

3.3. Irrigation

Previous archaeological research in the Zerqa Triangle has attested the existence of irrigation infrastructure (Van der Kooij, 2007; Kaptijn, 2009a, 2010). Until the 1960s an irrigation system was in use where three main canals tapped the Zerqa river and via a large number of secondary and tertiary canals distributed the water over the entire plain in small gravity-flow open canals. Physical remains of the main canals and location of the settlements allows tracing this system back into Mamluk (AD 1250–1516) and Roman-Umayyad (63 BC – AD 750) periods (Kaptijn, 2009a). Unfortunately, no canals dating to the Iron Ages have been found. However, the environmental circumstances of this region with its high temperatures, dry summer months and very frequent dry years make it impossible for a large community such as during the Iron Age to successfully inhabit this area year round.

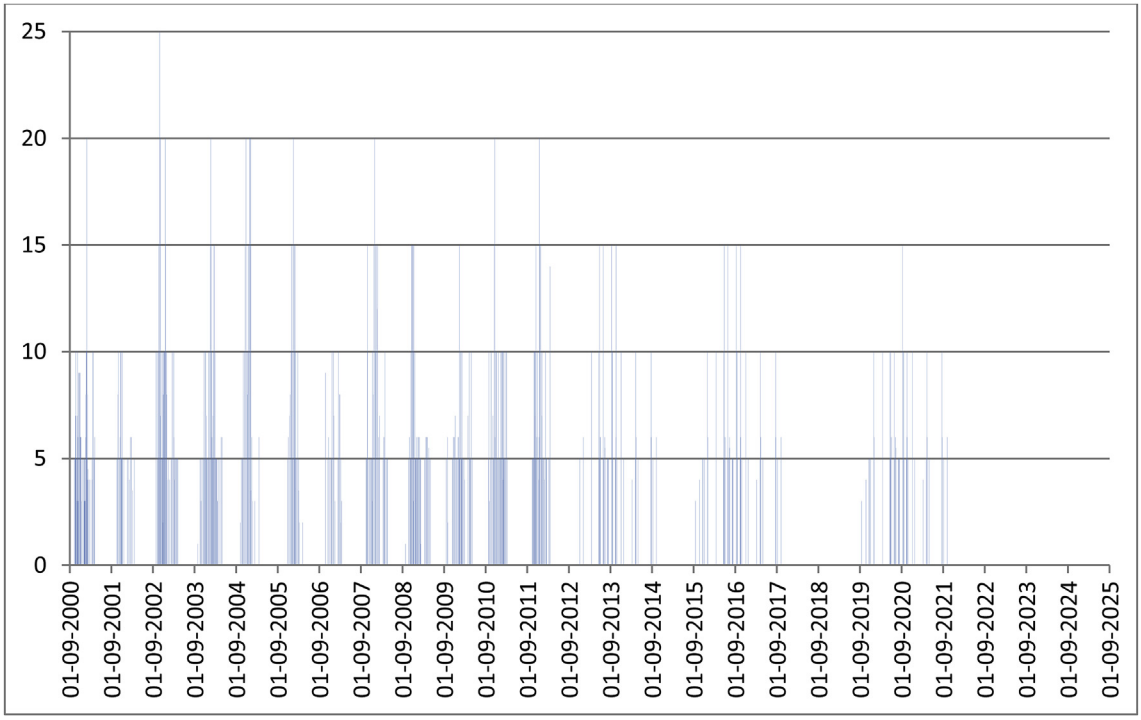

Fig. 5. Rainfall patterns used in the simulations (x-axis time, y-axis rainfall in mm).

Furthermore, plants requiring higher amounts of water than naturally available have been attested in archaeobotanical samples (Kaptijn, 2009a) and sites are located away from water sources (in contrast to preceding periods, see below) (Kaptijn, 2014). Especially the botanical samples of the Iron Age II period show species like flax that cannot be cultivated in this region without additional water (Van Zeist and Heeres, 1973; Neef, 1989, 2012). Even though no canals from this period are known, we can get a general idea of the layout of the system. The location of the settlements whose surrounding fields were supplied by the irrigation system in combination with physical constraints the canals have to adhere to (i.e. rock outcrops protruding from the hills and areas of higher elevation that have to be circumnavigated), suggests that the main or primary canals of the Iron Age were along broad lines located in the same places as the primary canals attested in later periods (see Fig. 4) (Kaptijn, 2009a) (a detailed description of the evidence for irrigation and the layout of the system can be found in Kaptijn, 2009a: 301–331). No evidence has been found of the use of cisterns to collect rainwater. Immediately north of the research area an Iron Age well has been excavated (Tubb, 1998: 85). This site is located on the edge of the *zor*, so on a much lower elevation and closer to groundwater. Still a massive structure was needed to reach groundwater at 8 m below the surface. In other areas of the Levant Iron Age wells or water tunnels have been found, e.g. at Megiddo reaching 40 m below the surface. These are very large structures which would have been found had they been present in the Zerqa Triangle. The deep incision of the Zerqa, already during the Late Bronze/Iron Ages, precludes the use of groundwater except perhaps for a few isolated locations in (old) alluvial fans near the foothills.

While there are several strands of evidence that irrigation was practised during the Iron Age, the evidence for the Late Bronze Age is less clear cut. Flax, for example, has also been found in Late Bronze Age layers at Deir ‘Allā, but only in very small quantities (Van Zeist and Heeres, 1973). The Late Bronze Age is the first period in which site locations appear to be less connected to natural water sources, as sites appear in the middle of the plain (Kaptijn, 2014). This move suggests other sources of water had to be mobilized. While irrigation may thus have been present in the Late Bronze Age, it is unknown whether it was well-developed until the Iron Age II period (c.1000 BC). Below, we develop some considerations why and how Zerqa inhabitants would have made the change towards irrigated farming.

4. Modelling water availability and crop yield

To understand the impact of environmental changes on the subsistence of communities, we can model different hypothetical scenarios and evaluate the difference in outcomes. This modelling will not be an exact reconstruction of the past, but the results provide more specific questions within better-defined boundaries to guide our thinking on past resilience. It is especially important to consider that the modelling specified below does not answer any question related to exact shapes and sizes of water systems, fields or farms. We have modelled water availability and resulting crop yields per standard unit of hectare. Where relevant we have distinguished between water available from rain, groundwater, soils or through adding water from an additional source. How all this water would have flowed to fields, however, is not what we discuss. Despite the importance of the question whether water could actually be delivered (see Ertsen, 2010 and Ertsen and van der Spek, 2009), in our current analysis we are interested in the impact of water availability in time and space, and not so much on how this water was delivered. As such, we use the term ‘irrigation’ as a generic concept meaning ‘bringing water to fields’ without specifying whether it would be river water through canals or rainwater harvesting systems.

4.1. Methodology

In our modelling, we have defined an artificial climatic record for a period of 25 years (see Table 2 and Fig. 5). This is probably much shorter than the period in which the climatic changes took place in reality. People in the past probably had more time to adapt to the changed circumstances. However, we are able to determine any changes in terms of water availability and yields that may have affected Zerqa farmers. Based on rainfall and temperature data collected in the 20th century (Jordan Meteorological Department, 1976–2016), a daily rainfall pattern has been created. The modern climate was taken as

Table 3
The different scenarios.

Scenario	Crop	Climatic data	Soil	Groundwater level	Starting conditions	Irrigation strategy	Observations in the model
1a	Standard wheat crop file with extended growing season between December 1 and May 19	Artificial climatic data series based on 20th century data	Standard Sandy Loam file	2 m below surface	Dry topsoil	None	No problem with crop growth
1b				3 m below surface			Crop growth drops quickly, some issues in dry years
1c				4 m below surface			Crop growth less than GW-3 and only slightly higher than GW-10.
2				10 m below surface	Dry topsoil	None	Dry years result in much lower yields
3					Dry topsoil	Allowing 50% depletion of Ready Available Moisture	No problem with crop growth, but irrigation demands are high.
4					Field capacity	None	No clear difference with rain-fed scenario
5					Field capacity	100 mm after 30 days	Biomass shows some improvement in numbers
6					Field capacity	100 mm after 60 days	Biomass and yields show higher numbers

starting point. We do not know exactly what the climate looked like before the arid period. There are, however, indications that this was not very different from the present-day situation (Neumann et al., 2007; Litt et al., 2012). As (changes in) potential evaporation and temperatures are more difficult to define per day and their daily impact is less important, their values have been kept monthly.

Two series of simulations have been run. In the first series (A), the second half of the series has been made drier and warmer. In the second (B), the latter half was made drier, but not warmer as climate proxy data do not agree on the variation in temperature. Because it is difficult to determine how much drier the ancient climate would have become exactly, rainfall numbers have been decreased with 1, 2 and 3 mm per event in three periods respectively (Fig. 5). Temperatures and evaporation have been increased with 5 and 10% respectively. To allow a certain variation per year, a weight factor between 0.9 and 1.1 has been assigned to each year (see Table 2). As such, we have an artificial climatic record in terms of exact parameter values and length. That record allows us to find out when and to what extent yields from farming in the Zerqa area would be affected by changes in rainfall and/or temperature.

Using a crop growth model, different scenarios have been defined – with variations in groundwater level and crop treatment in terms of water (see Table 3). AquaCrop, the standard crop growth model developed by the Land and Water Division of the Food and Agricultural Organization, simulates plant yield response to water, in particular to address conditions where water is a key limiting factor in crop production. AquaCrop uses a relatively small number of explicit parameters, but the calculation procedures is grounded on biophysical processes to guarantee accurate simulations.

We have applied the standard AquaCrop crop data for wheat, with a growing season starting on December 1 (Table 3). The resulting crop growth are shown as values for biomass and dry yield (edible part of the crop for modern crops). The numbers produced by our modelling would be valid for modern crops, and as such cannot be used directly. As we are interested in the comparative aspect, that is the difference in crop success between different climatic scenarios, the absolute crop numbers have been scaled in percentages with the highest yields of the most critical rain-fed scenario as the 100% reference. Furthermore, as it is reasonable to assume that ancient crops were both more drought-prone – particularly when setting fruit – and had different relations between total biomass and dry yield – with biomass being a better indication for total crop success compared to the effective dry yield of grain – we assume that biomass generation is a good proxy for crop success. Groundwater levels were set at varying depths, to study to what extent capillary water delivery from the subsurface could compensate for lower rainfall. Different starting conditions for farming were defined, in terms of water availability in the topsoil. Finally, different irrigation strategies were defined as well, in order to see how farmers might have responded to potential water deficits. We compared scenarios with fixed water amounts after a certain amount of time to a situation where a farmer would provide water to the field when the amount of water available to the crop fell between a threshold of 50% (Ready Available Moisture 50% depleted).

5. Results

The resulting crop numbers suggest that with current climatic conditions, rain-fed agriculture would have been a rather successful strategy for growing crops in the area (Fig. 6, years 1–12). Although yield variations can be observed – with percentages to reference roughly between 80 and 50 – over a longer period the average yield is stable. To overcome shortages due to occasional dry years, storage facilities to bring surplus from one year to another would be required. As soon as the drier and warmer years start, however, stability is no longer guaranteed – at least not in terms of dry yields. What happens depends on the environmental conditions that we define. Fig. 6 presents biomass

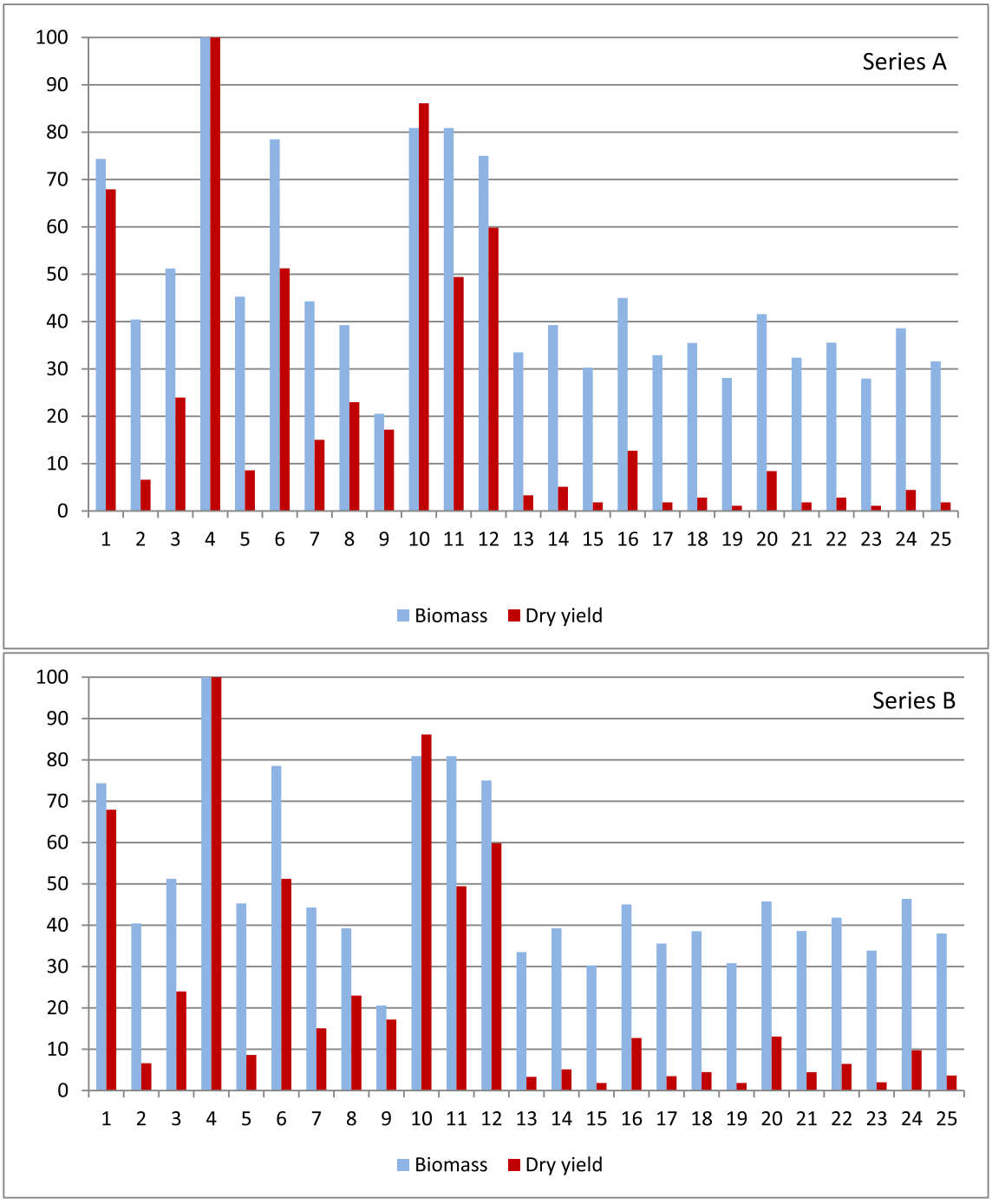

Fig. 6. Crop yields under rain-fed agriculture with groundwater at 10 m below the surface (x-axis time, y-axis percentage).

and dry yield results with a low groundwater level. As there is clearly no capillary rise from that same groundwater, the crop suffers from increasing aridity. As soon as the drier years appear, dry yields in our model drop rather dramatically – with dry yield numbers as low as only a few percentages of the reference year (see Fig. 6, years 13–25). Biomass figures, on the other hand, stay on the lower spectrum of the earlier wetter period – with the really high peaks disappearing – but all years still produce biomass. Crops would still grow within a climate becoming more arid.

When we assume that local groundwater levels are high, however, Fig. 7 suggests that there does not seem to be any huge response to crop yields with increasing aridity – and as such biomass will not respond either. The highest groundwater level of 2 m below surface appear to bring enough water to the root-zone through capillary rise to sustain biomass and dry yields. However, as soon as the groundwater level drops one additional meter, yields drop considerably and only wet years show higher yields. Groundwater levels of 4 m and 10mbelow the surface are very similar to 3 m below the surface and do not yield large differences in terms of crop growth. We conclude that groundwater, with the exception when it is at 2 m below surface, is unable to sustain crop growth when the climate becomes more arid.

Adding additional water before and during the growing season can help, but not necessarily. Not surprisingly, developing an irrigation strategy based on refilling the total soil moisture that would be available to the crop in its root zone – in our scenario after 50% of that same moisture would have been used – results in extremely high crop yields –

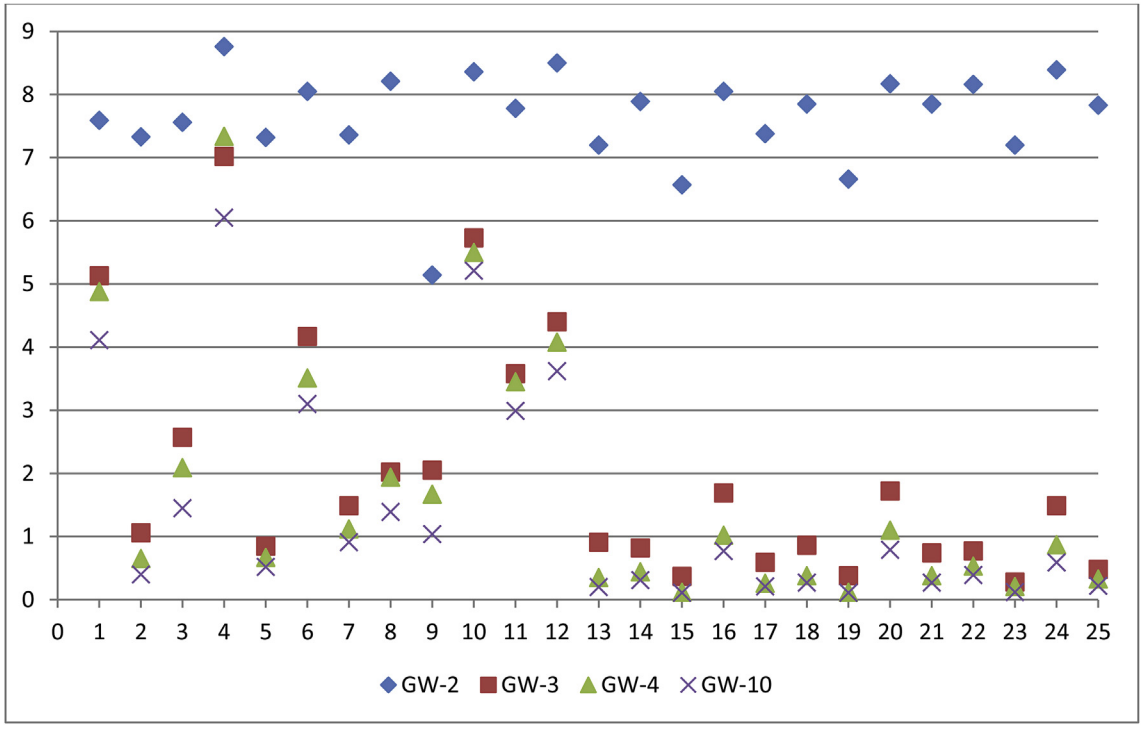

Fig. 7. Dry yields in rain-fed agriculture for different groundwater levels (x-axis time, y-axis tons/hectare).

with yields actually becoming higher in drier and warmer conditions, as crops presumably can transpire more. Obviously, the required irrigation amounts to sustain these huge yields rise as well – with values becoming rather unrealistic over time. In addition, the irrigation schedules become complex in terms of timing. These two factors suggest to us not to consider this strategy as realistic, both in terms of complexity and in terms of easy response to change. It is reasonable to expect that a first response to change in terms of lower yields will not be an immediate move to a complex schedule of watering fields with huge amounts of water.

In line with what we have argued earlier (Ertsen and Kaptijn, 2015), we consider other types of irrigation strategies more likely – especially those based on saturating the soil with water just before the growing season to allow the young crop to develop – a strategy that can be achieved by systems as different as 'canal irrigation' and 'water harvesting'. Such a strategy mobilizes only limited amounts of water and allows for fairly straightforward and controllable irrigation management strategies. We have applied three different sub-scenarios for this type of irrigation: 1) securing saturated soil at the start of the cropping season (which implies already one artificial water transfer to the field before sowing); 2) securing saturated soil plus one additional water gift after 30 days; and 3) securing saturated soil plus one additional gift after 60 days.

When we apply the scenario with only saturated soil (field capacity of the soil – scenario 4) at the start of cropping activities, we do observe somewhat higher biomass numbers, but the rainfall afterwards is clearly not able to sustain crop growth in such a way that it results in larger amounts dry yield. As we mentioned above, the value of dry yields from a modern crop model may be less strict for ancient crops, but we would still argue that the difference between non-saturated and saturated starting conditions is rather low to define this strategy as a possible success.

As soon as one additional irrigation gift of 100 mm is added (scenario 5), however, we do observe higher yields – again especially in biomass and also for some years in the wetter first years (see Fig. 8). Although yields do not reach pre-change values, the biomass values are fairly stable and not that much lower than many in the wetter rain-fed conditions. We also observe how important the timing of the irrigation gift would have been. Irrigating 30 days after sowing (Fig. 8) does boost biomass somewhat, but does not really add to the dry yield results – much of the extra water would have disappeared anyway before the maturing crop could have used it. Irrigating once after 60 days produces higher biomass and dry yield figures (scenario 6) (Fig. 9).

Overall we conclude that, as could be expected, the scenarios with all climatic factors becoming worse for plant growth (decreased rainfall, increased evaporation, increased maximum temperature) result in lower plant growth as expressed in biomass and dry yield (see Figs. 6, 8 and 9). When yields of the two climate series are compared, the differences seems large. For example, in year 25 of our simulations, under rain fed agriculture with low groundwater levels, the dry yield of crops receiving less rainfall, but higher temperatures and more evaporation are only half of the dry yield of crops that just have to cope with increasing aridity (see Fig. 10–1). While the differences between crops grown under scenarios with and without increasing temperatures and evaporation seem large when expressed in percentages, the largest differences in terms of yields and biomass are found between high and low groundwater levels. If the groundwater level was below 2 m under the surface, farming will have become difficult in all scenarios, also when the climate only became drier and not warmer.

6. Discussion

Although the crop and water calculations could be much more detailed and are based on modern instead of ancient climate data, we would argue that we have captured some important dilemma's for farmers that are confronted with changes in climate in terms of increasing temperatures and/or decreasing rainfall – and some rather important issues to be considered by those who study them. Please note that we do not deal with the question how a farmer would detect that anything was changing in the first place, as this question is rather complex (see Ertsen and Wouters, 2018). The issues we present below are a first step towards such a more comprehensive analysis of possible detection of change and potential strategies to deal with such change based on more extensive modelling as presented in Ertsen (2016) and

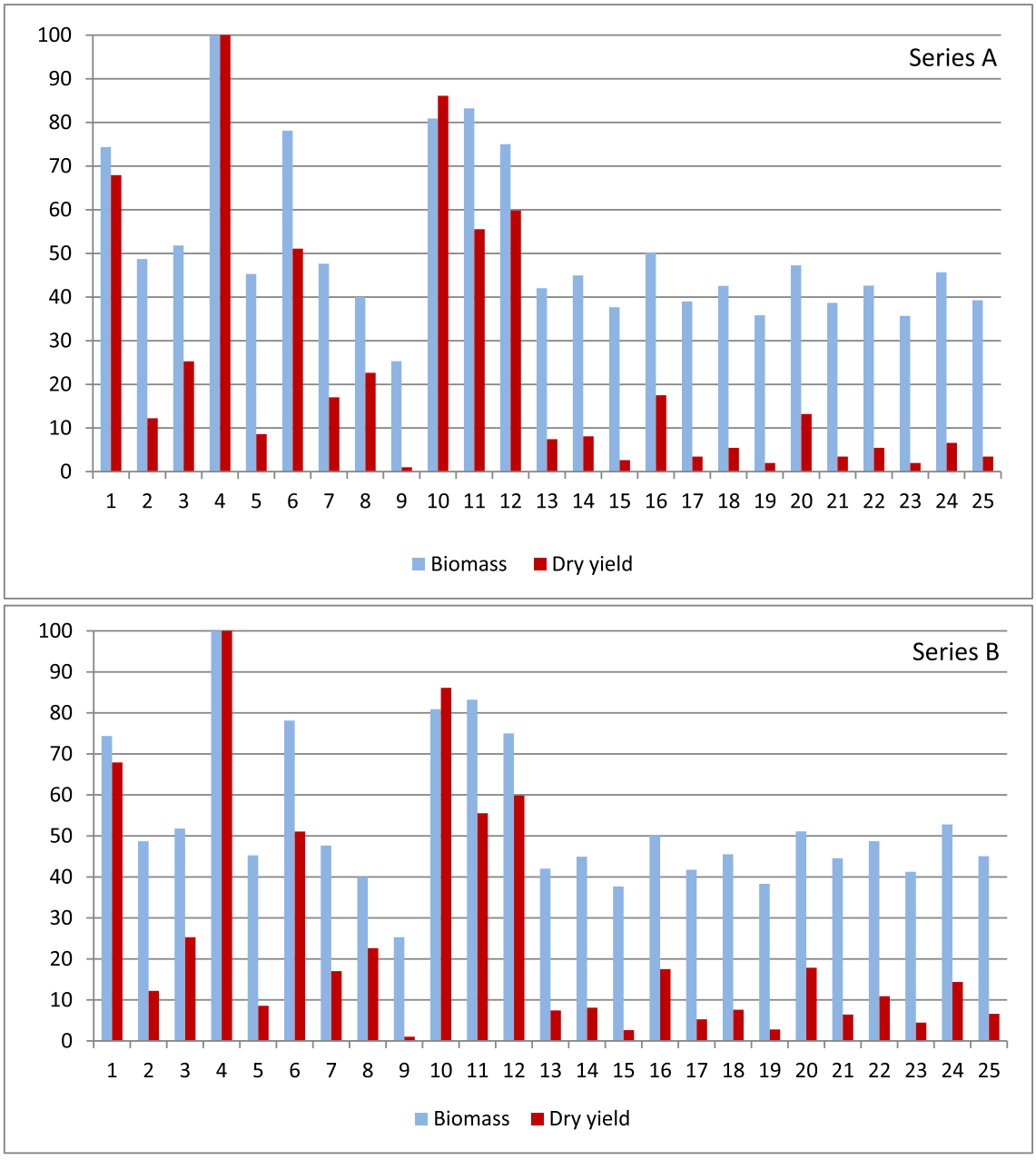

Fig. 8. Crop yields under rain-fed agriculture with Field Capacity at the start of the cropping season and one 100 mm irrigation feed after 30 days with groundwater at 10 m below the surface (x-axis time, y-axis percentage).

Zhu et al. (2018).

A first issue is what the environmental conditions would have been when the climate started to change. In our case, especially the groundwater and the general moisture availability appear to be of importance. Only when the groundwater is as high as 2 m below the surface, sufficient moisture is available to cope with increasing aridity. It is, however, unlikely that the groundwater was ever that high in this region. Today, groundwater is only found 30–100 m below the surface, but this is due to overexploitation by motorized pumps (Nedeco and al-Handasah, 1969: table B-40; Van der Steen, 2004: 32). Although we do not have detailed groundwater levels for the Late Bronze and Iron Age, archaeology does provide some indications. At ed-Dayyāt, in the research area on the northern bank above the incised river Zerqa, an Iron Age I silo has been excavated (1210–970/960 to 940 cal. BC). This silo had a depth of 1.97 m below the ancient surface and no traces of water could be identified (Kaptijn et al., 2011: 152). Additionally, at Tell es-Sa'idiyyeh, located 3.5 km north of our research, an extensive water well dating to the 12th century BC was discovered going down c.8 m below the valley plain Tubb (1998: 85). Tell es-Sa'idiyyeh is located on the edge of the *zor*, the actual streambed of the Jordan river located c. 40 m below the area under discussion here. This suggests that the Late Bronze Age/Iron Age groundwater in the Zerqa Triangle lay well below the level that allowed plants to benefit from it. Furthermore, geomorphological investigations have attested that a major downcutting episode had already taken place before the Late Bronze/Iron Age and the Zerqa and Jordan rivers were already deeply incised (see above).

A second issue – and a major dilemma of farmers – is which cropping strategy would have been practised at the change from wetter to drier conditions. Although rain-fed farming seems to have been possible before the onset of aridification, irrigating the crops in drier years before our climatic change in the model would have sustained higher yields as well. If such a strategy of artificially watering fields was

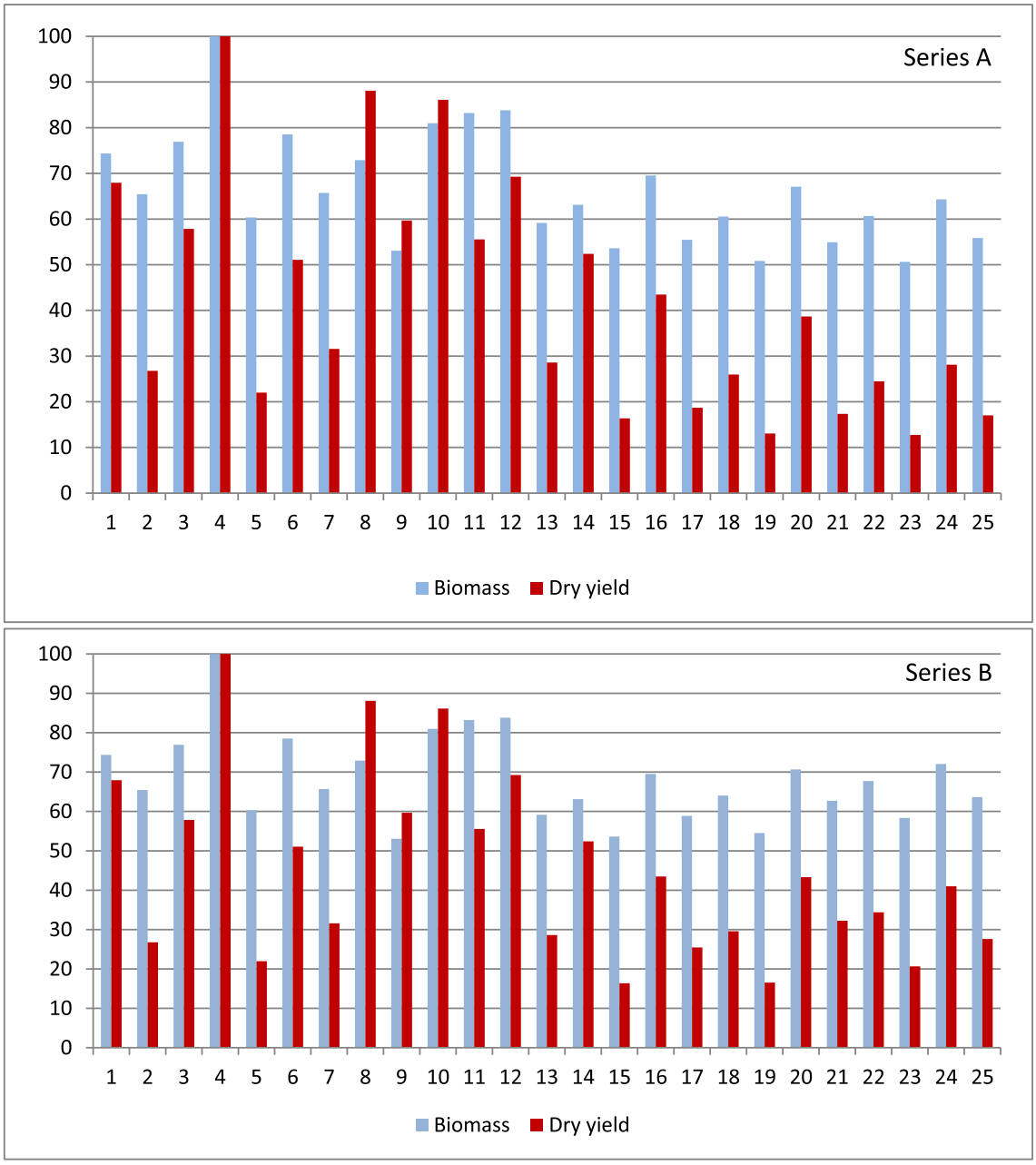

Fig. 9. Crop yields under rain-fed agriculture with Field Capacity at the start of the cropping season and one 100 mm irrigation feed after 60 days with groundwater at 10 m below the surface (x-axis time, y-axis percentage).

practised already before climatic change, farmers would need to continue using it every year with increasing aridity. This would obviously ask more labour input throughout the year, but would also yield relatively stable harvests.

If irrigation was not practised yet, we could presume that increasingly drier conditions may have led farmers to think about diverting some of the supply from rivers and wadi's to their fields, or find other ways to bring water to their fields. To what extent this was possible – in terms of flows in rivers, rain water harvesting techniques or labour needed to bring water to fields, etcetera – we cannot be certain and much more work is needed, but we can assume that farmers would observe floodplain vegetation growth and as such may have tried to mimic that. It is likely that people in this region were well aware of the impact of water on crop growth. There is evidence for floodwater farming during the Late Chalcolithic and Early Bronze Ages I-II (c.4600-3600/3600-2700 BC). At that time, rivers and wadis were not as deeply incised as they are today and were in the Iron Age. Rivers overflowed seasonally in a moderate, low intensity fashion (Hourani, 2010). The location of settlements and overflow deposits suggest people used these flood plains to cultivate crops, potentially using walls to retain the water longer (Kaptijn, 2009a: 326–337). After the Early Bronze Age the river regime changed and floodplain cultivation became more difficult as a result of higher stream velocity and down cutting of river beds (Hourani, 2008, 2010). Although completely different from canal irrigation, water management techniques had thus been available to the inhabitants of the Zerqa Plain for a long time.

7. Conclusions

The archaeological remains of the Zerqa region show both continuity and change. Sites are abandoned or show instability with a rapid succession of abandonment/destruction and resettlement, but the

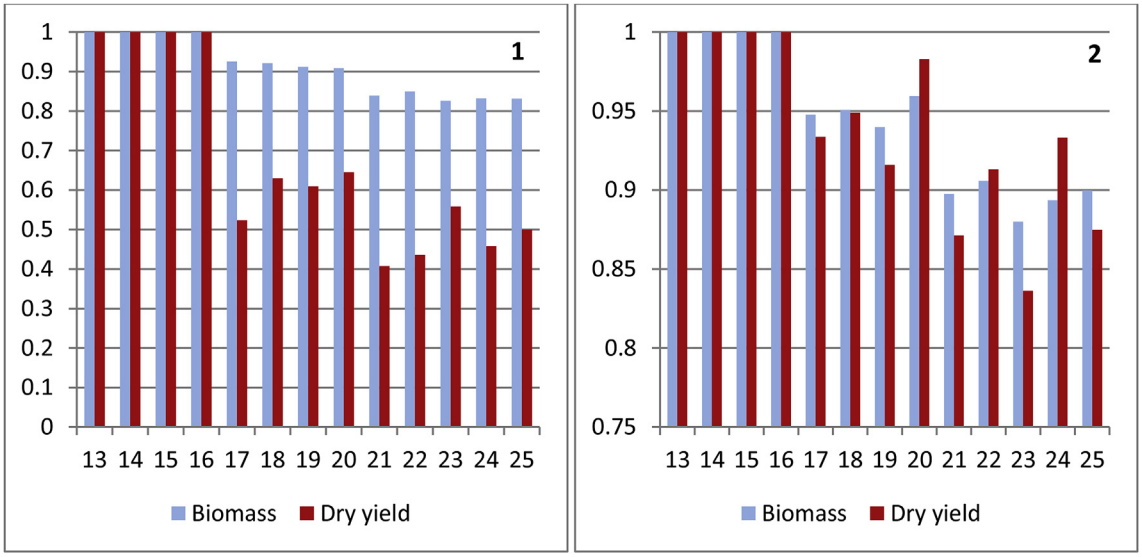

Fig. 10. Ratio between plant growth in two different climate scenarios (series A - aridification with temperature/evaporation increase and series B - aridification only) 1 - rain-fed growth with low groundwater, 2 - rain-fed growth with high groundwater (x-axis time, y-axis dimensionless).

region as a whole is characterized by continuity of habitation. The present state of excavation does not allow differentiation of the weight of the underlying causes, i.e. aridification, earthquakes, diminished regional trade, social unrest in the wider region. It is, however, clear that all these factors will have impacted communities living in the Zerqa Triangle.

Our analysis suggest that the inhabitants of the Zerqa Triangle will have felt the impact of the more arid conditions that occurred at the end of the Late Bronze Age. As it is likely that the groundwater level never reached as high as the 2 m below the surface that our model suggests as crucial for sustained crop development, climatic changes will have been felt. Even in the case that we allowed temperatures and therefore evaporation to stay the same, just increasing aridity would have been enough to put crop growth under severe stress. The occasional drier years that characterize this region even in less arid conditions, will have become more frequent, reaching a point where storage of surplus yields from year to year would not have been a feasible strategy anymore – as surpluses became scarce. Our scenarios and calculations are based on the assumption that the present-day climate is comparable to the starting conditions during the Late Bronze Age. Indeed, climate reconstructions and attested natural vegetation suggest that the early Late Bronze Age climate was most likely not dramatically different from that of today.

Our computations may have been rather basic, but our numbers suggest that more intensive irrigation – again, defined as bringing additional water to fields without specifying exactly how - in the aridifying Zerqa Triangle could indeed have grown from rain-fed agriculture that already applied additional water to support crop growth in wetter times to cope with drier years. Obviously, such a change from rain-fed basics with some extra irrigation to irrigation-based farming would have asked for changes in labour input and coordination, but does not seem to have been impossible in the drier and warmer climate. Whether irrigated farming could have developed fast enough from a completely rainfed farming system is a question we cannot answer with our current analysis, as this required a more fine-grained (modelling) analysis of yields, flows and fields.

Even so, there is evidence for large-scale use of irrigation – with the suggestion of canals transporting water into the Zerqa area - from the Iron Age II onwards (c. 1000 BC). Although we have insufficient evidence at present to draw firm conclusions, we might tentatively consider the aridification attested between the 13th and 10th century BC as the trigger that led communities in this area to develop their less labour-intensive form of water management into an irrigation system in order to maintain a sustainable mode of subsistence. When moister conditions returned during the Iron Age II and habitation grew more intensive and permanent, irrigation may have developed into a mode of subsistence that allowed intensive cultivation including water dependent crops like flax. More research is needed to test this hypothesis. However, our modelling shows that irrigation would have been able to increase the resilience of Zerqa farming communities on the edge between the desert and the sown. The climatologically adverse conditions at the end of the Late Bronze Age may thus have instigated a system that in terms of crop yield proved to be very productive, especially during later, climatologically more advantageous, i.e. moister, periods. The Late Bronze Age aridification can therefore be taken as case in point of the Arabic proverb ‘all sunshine makes a desert’.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jaridenv.2018.11.006.

Conflicts of interest

The authors have no conflicts of interest.

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